Advancing physics simulations at a Multi-TeV Muon Collider

APS April Meeting 2021

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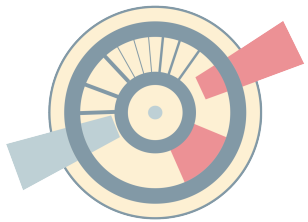
April 18, 2021



[1] with A. Costantini, F. De Lillo, F. Maltoni, L. Mantani, O. Mattelaer, X. Zhao

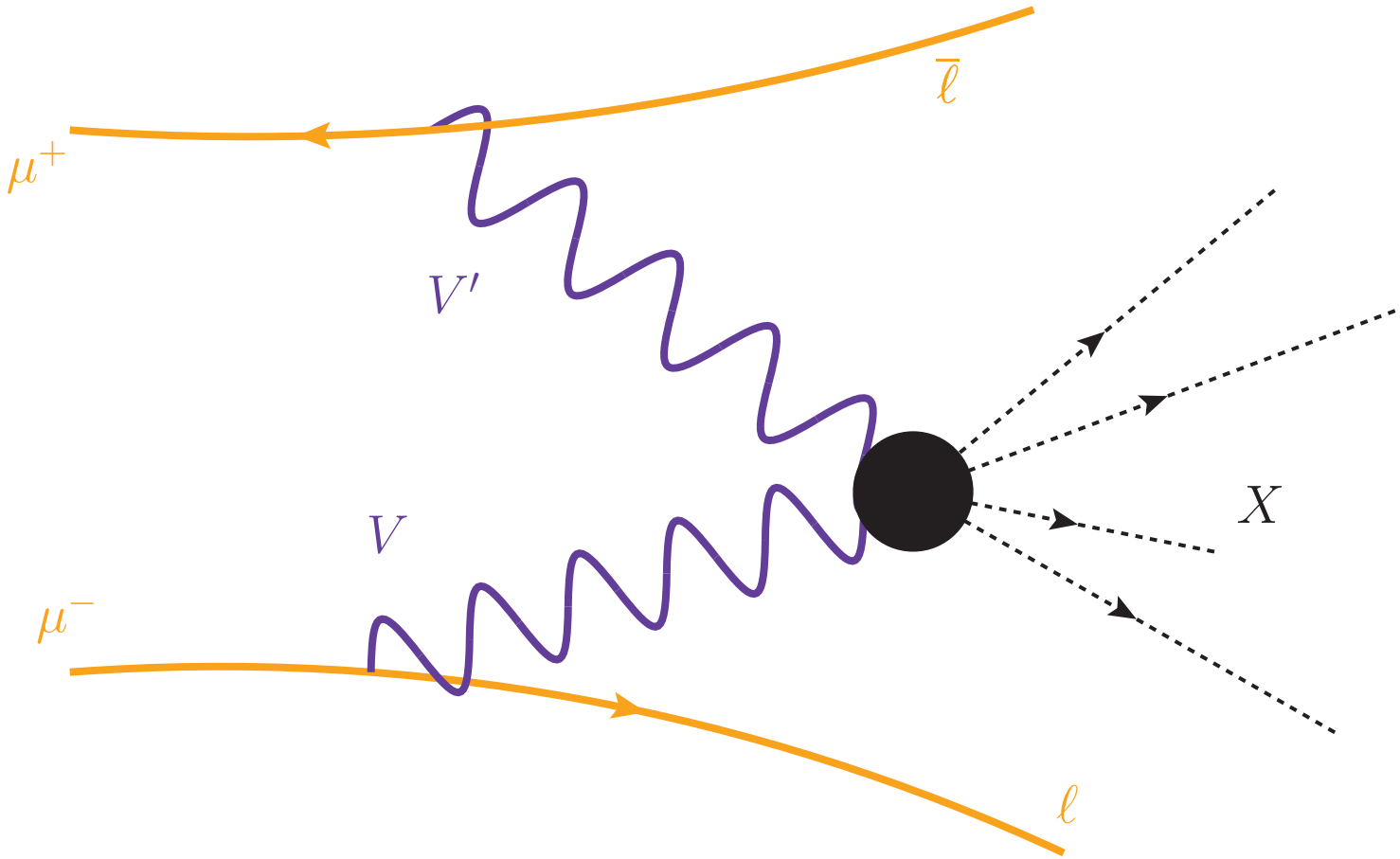
Disclaimer: this talk is **is not** about technical aspects of **Monte Carlo (MC)** event generation in high energy physics

Disclaimer: this talk is **is not** a tutorial

Disclaimer: this talk **is** about exploring the physics potential of a future $\mu^+\mu^-$ collider given better MC tools[2]

[2] w/ A. Costantini, et. al., JHEP('20) [arXiv:2005.10289] + *to appear*

the big question why a $\mu^+\mu^-$ collider?



The many motivations for a muon collider

- **Generically,** discovering laws of nature requires larger data sets and higher energies

  See Xie's talk today and, e.g., Al Ali, et al. [2103.14043]

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- **Uniquely,** $\mu^{\pm}$ colliders **directly** probe the nature of $\mu^{\pm}$ flavor itself
  - context: present flavor anomalies are arguably "μ-flavor" anomalies

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- **Excitingly,** *partonic* collisions at $Q \sim \mathcal{O}(10)$ TeV explore when electroweak (EW) symmetry is nearly restored, i.e., $M^2_{W/Z/H}/Q^2 \to 0$
  - our role: updating mainstream simulation software (`MadGraph5`) to handle challenges of $\mathcal{O}(10)$ TeV collisions

  This talk and, e.g., Chen, et al [1611.00788] and Han, et al [2007.14300]

MadGraph5_aMC@NLO (mg5amc) in a Nutshell

In a Nutshell

MG5aMC is the 5th (or 6th) iteration of the Monte Carlo (MC) event generator `MadisonGraph` (or `MadGraph`) by Stelzer and Long at Wisconsin [hep-ph/9401258]

- For a given scattering process, generates Feynman Graphs and helicity amplitudes (`HELAS` routines) for *fast* numerical determination of rates

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- + arbitrary color structures, + spin correlated decays of resonances (`MadSpin`), + amplitude support for arbitrary Feynman Rule (`ALOHA`), +jet matching/merging, + loop-induced processes (`MadLoop`)

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- + arbitrary color structures, + spin correlated decays of resonances (`MadSpin`), + amplitude support for arbitrary Feynman Rule (`ALOHA`), +jet matching/merging, + loop-induced processes (`MadLoop`)
- Merger with `MC@NLO` for NLO in QCD [1405.0301] and NLO in EW [1804.10017]

So what is new?

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- Matrix elements **(ME)** and cross sections for external partons with fixed helicity polarizations
  w/ D. Buarque Franzosi, O. Mattelaer, S. Shil [1912.01725]

- Enabled default configurations for $\mu^+\mu^-$ collisions
  w/ A. Costantini, F. De Lillo, F. Maltoni, L. Mantani, O. Mattelaer, X. Zhao [2005.10289]

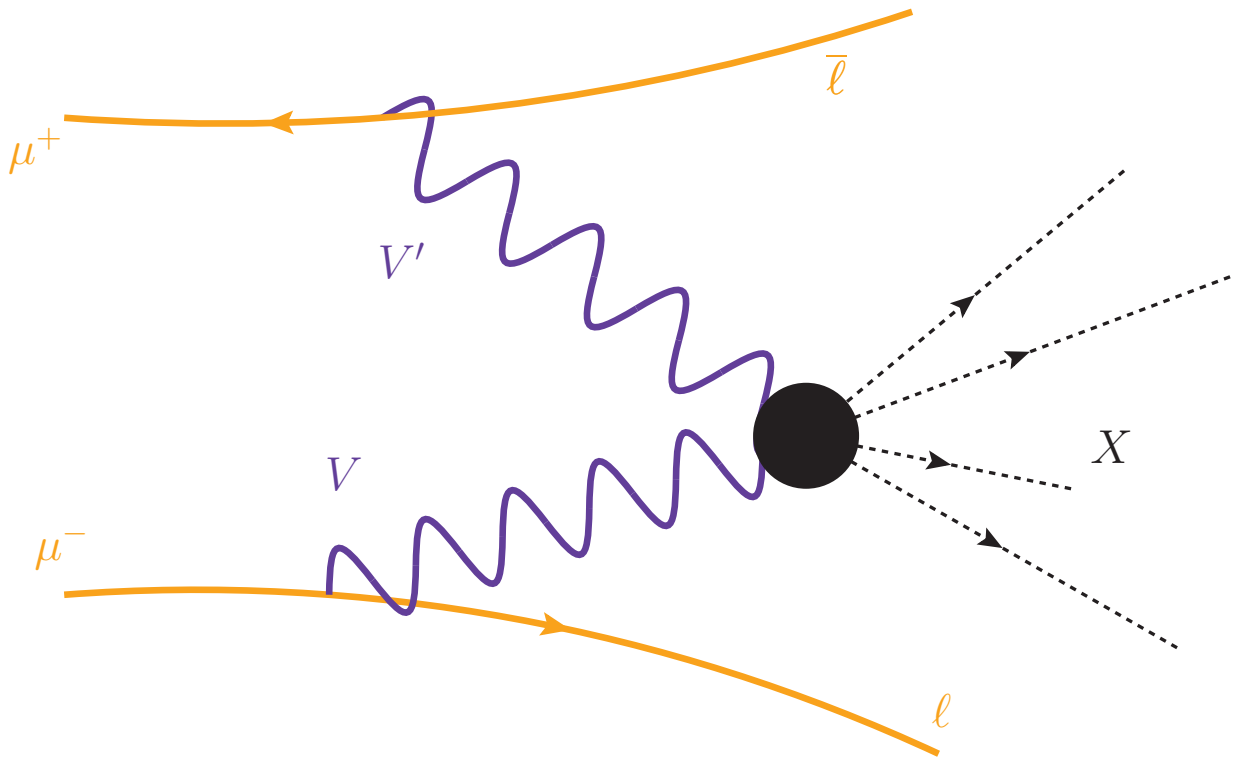
- Better phase space integration routines for t-channel momentum transfers
  K. Ostrolenk and O. Mattelaer [2102.00773]

- More efficienct evaluation of ME with many external legs
  K. Ostrolenk and O. Mattelaer [2102.00773]

- EW boson parton distribution functions for lepton colliders
  w/ A. Costantini, F. Maltoni, L. Mantani, O. Mattelaer [2105.?????]

A lot!
However, no time, so focus on results!

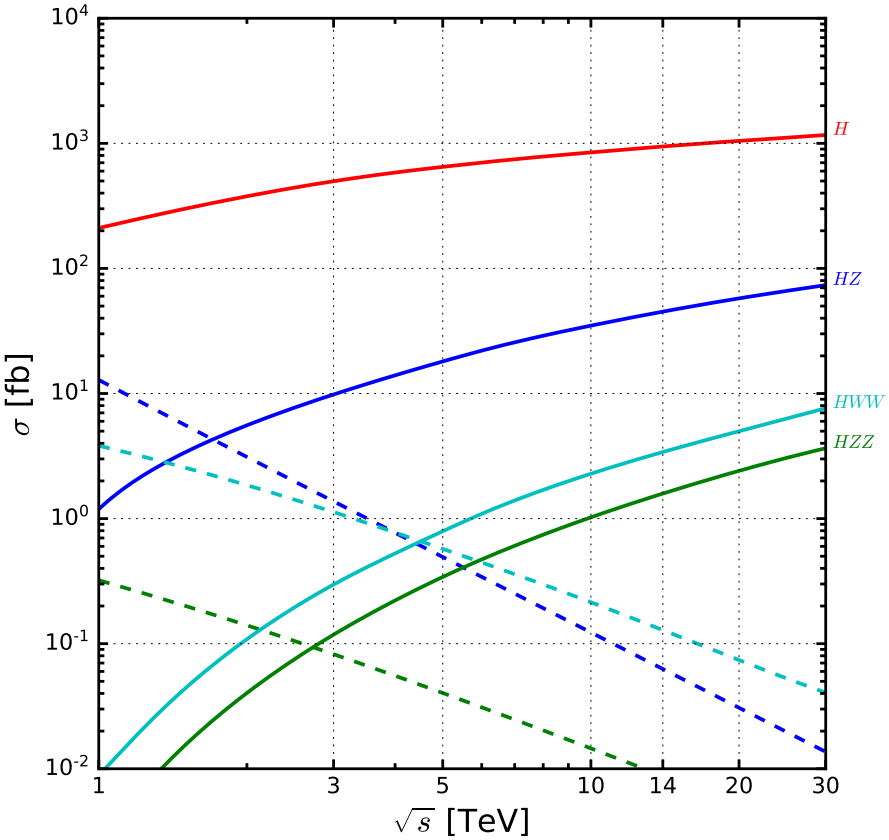
vector boson fusion/scattering (VBF) vs s-channel annihilation in multi-TeV muon collisions[3]

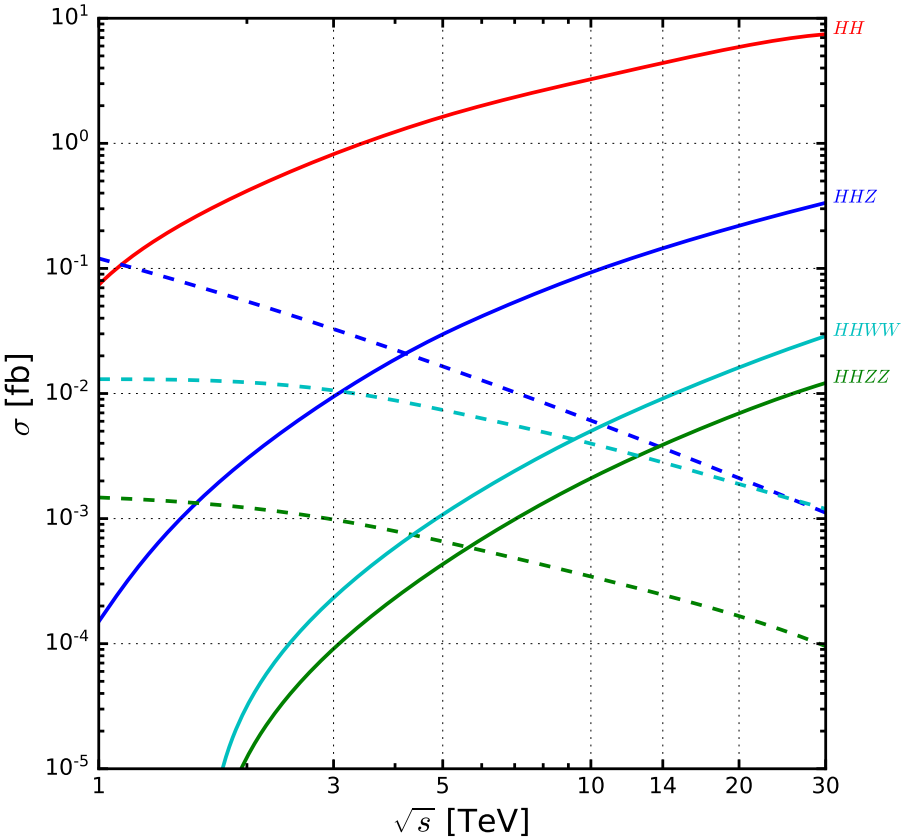


[3] w/ A. Costantini, F. De Lillo, F. Maltoni, L. Mantani, O. Mattelaer, X. Zhao [2005.10289]

Higgs production

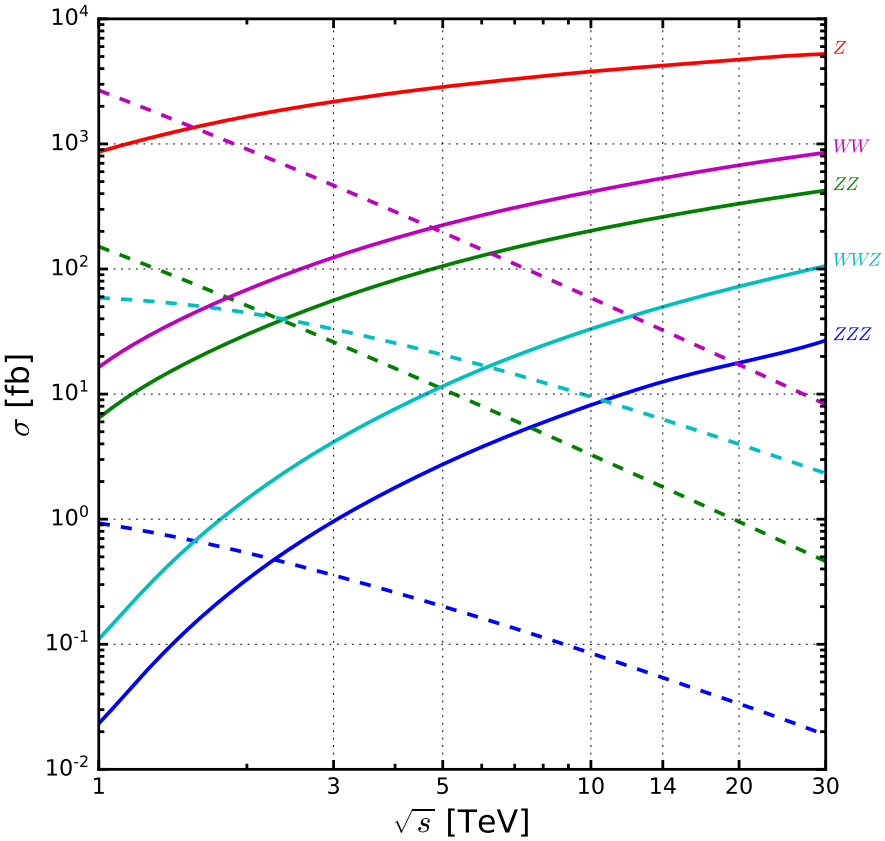
cross sections (σ) vs $\sqrt{s}$ for s-channel annihilation (dash) vs VBF (solid)

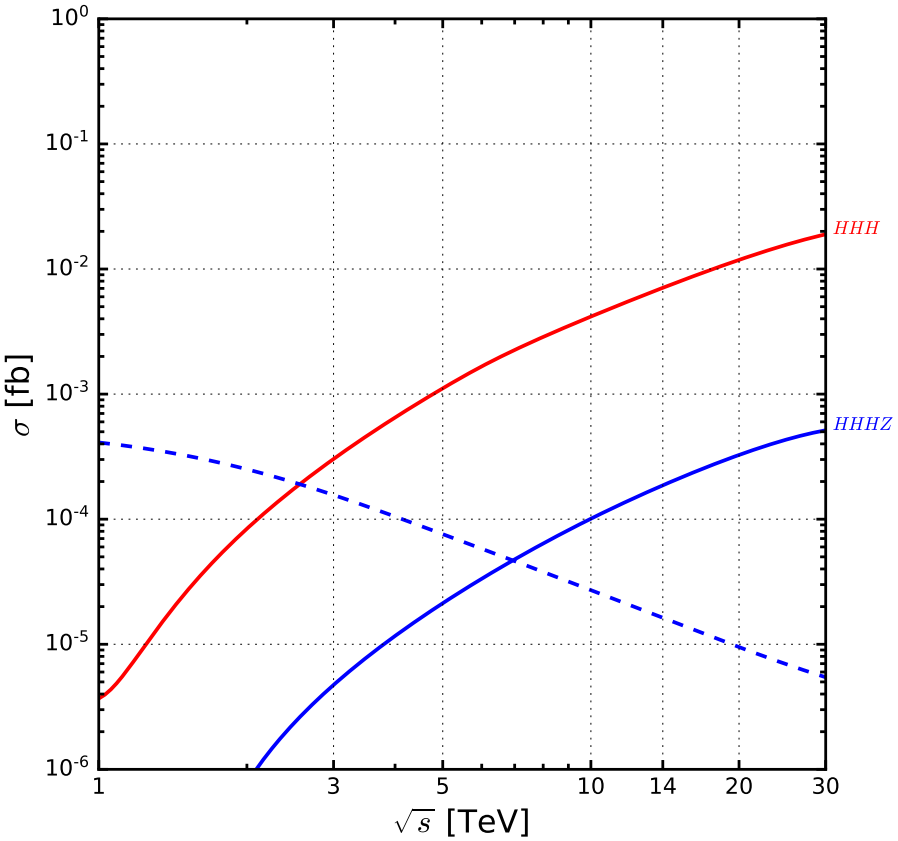




- $\sigma^{VBF} > \sigma^{s-channel}$ since
  - $\sigma^{s-channel} \sim 1/s$
  - $\sigma^{VBF} \sim \log^2(Q^2/M_V^2)/s$ due to forward emission of $V = W/Z$

Many-boson production





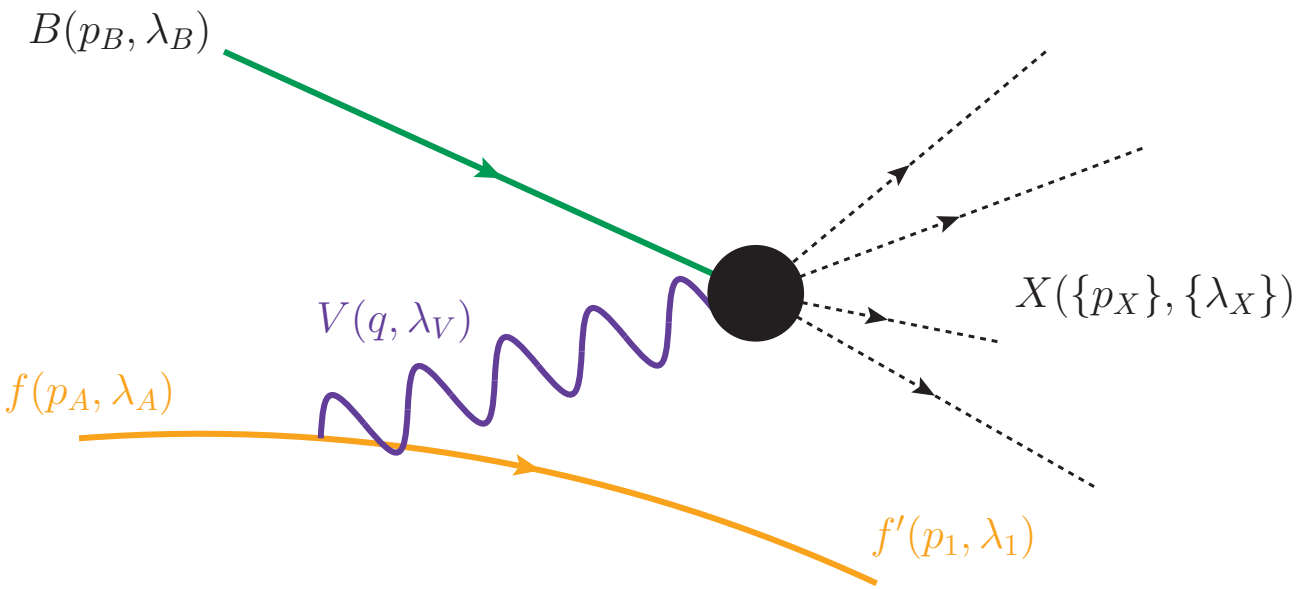
- Eventually, **VBF is dominant** production vehicle of EW states
- Evidence that **dominance is universal** and occurs at $\sqrt{s}$ for

w/ A. Costantini, et al [2005.10289]

$$\frac{\sigma^{\rm VBF}}{\sigma^{s-ch.}} \sim \mathcal{S} \left(\frac{g_W^2}{4\pi}\right)^2 \left(\frac{s}{M_X^2}\right) \log^2 \frac{s}{M_V^2} \log \frac{s}{M_X^2} > 1$$

see backup for more plots!

NEW Effective Vector Boson Approximation (EVA): EW bosons as partons of the $\mu^{\pm}$[4]



[4] w/ A. Costantini, F. Maltoni, L. Mantani, O. Mattelaer, et al [soon]

At very high scales $Q \gg M_W, M_Z$, EW bosons can be treated as partons

a.k.a. the Effective W Approximation [Dawson('84); Kane, et al ('84); Kunszt and Soper ('88)]

- Treatment of V_T identical to gluons in QCD; V_0 is novel complication
- W/Z PDFs will be released very soon in MadGraph5

$$f_{V_+/f_L}(z,\mu_f^2) = \frac{g_V^2}{4\pi^2}\frac{g_L^2(1-z)^2}{2z}\log\left[\frac{\mu_f^2}{M_V^2}\right],$$

$$f_{V_-/f_L}(z,\mu_f^2) = \frac{g_V^2}{4\pi^2}\frac{g_L^2}{2z}\log\left[\frac{\mu_f^2}{M_V^2}\right],$$

$$f_{V_0/f_L}(z,\mu_f^2) = \frac{g_V^2}{4\pi^2}\frac{g_L^2(1-z)}{z},$$

$$f_{V_+/f_R}(z,\mu_f^2) = \left(\frac{g_R}{g_L}\right)^2 \times f_{V_-/f_L}(z,\mu_f^2)$$

$$f_{V_-/f_R}(z,\mu_f^2) = \left(\frac{g_R}{g_L}\right)^2 \times f_{V_+/f_L}(z,\mu_f^2)$$

$$f_{V_0/f_R}(z,\mu_f^2) = \left(\frac{g_R}{g_L}\right)^2 \times f_{V_0/f_L}(z,\mu_f^2)$$

```
59  c     /* ****************************************************** *
60  c     EVA (1/6) for f_L > v_+
61        double precision function eva_fL_to_vp(gg2,gL2,mv2,x,mu2,ievo)
62        implicit none
63        integer ievo              ! evolution by q2 or pT2
64        double precision gg2,gL2,mv2,x,mu2
65        double precision coup2,split,xxlog,fourPiSq
66        data fourPiSq/39.47841760435743d0/ ! = 4pi**2
67
68  c      print*,'gg2,gL2,mv2,x,mu2,ievo',gg2 !3,gL2,mv2,x,mu2,ievo
69        coup2 = gg2*gL2/fourPiSq
70        split = (1.d0-x)**2 / 2.d0 / x
71        if(ievo.eq.0) then
72           xxlog = dlog(mu2/mv2)
73        else
74           xxlog = dlog(mu2/mv2/(1.d0-x))
75        endif
76
77        eva_fL_to_vp = coup2*split*xxlog
78        return
79        end
80  c     /* ****************************************************** *
81  c     EVA (2/6) for f_L > v_-
82        double precision function eva_fL_to_vm(gg2,gL2,mv2,x,mu2,ievo)
83        implicit none
84        integer ievo              ! evolution by q2 or pT2
85        double precision gg2,gL2,mv2,x,mu2
86        double precision coup2,split,xxlog,fourPiSq
87        data fourPiSq/39.47841760435743d0/ ! = 4pi**2
88
89        coup2 = gg2*gL2/fourPiSq
90        split = 1.d0 / 2.d0 / x
91        if(ievo.eq.0) then
92           xxlog = dlog(mu2/mv2)
93        else
94           xxlog = dlog(mu2/mv2/(1.d0-x))
95        endif
96
97        eva_fL_to_vm = coup2*split*xxlog
98        return
99        end
```

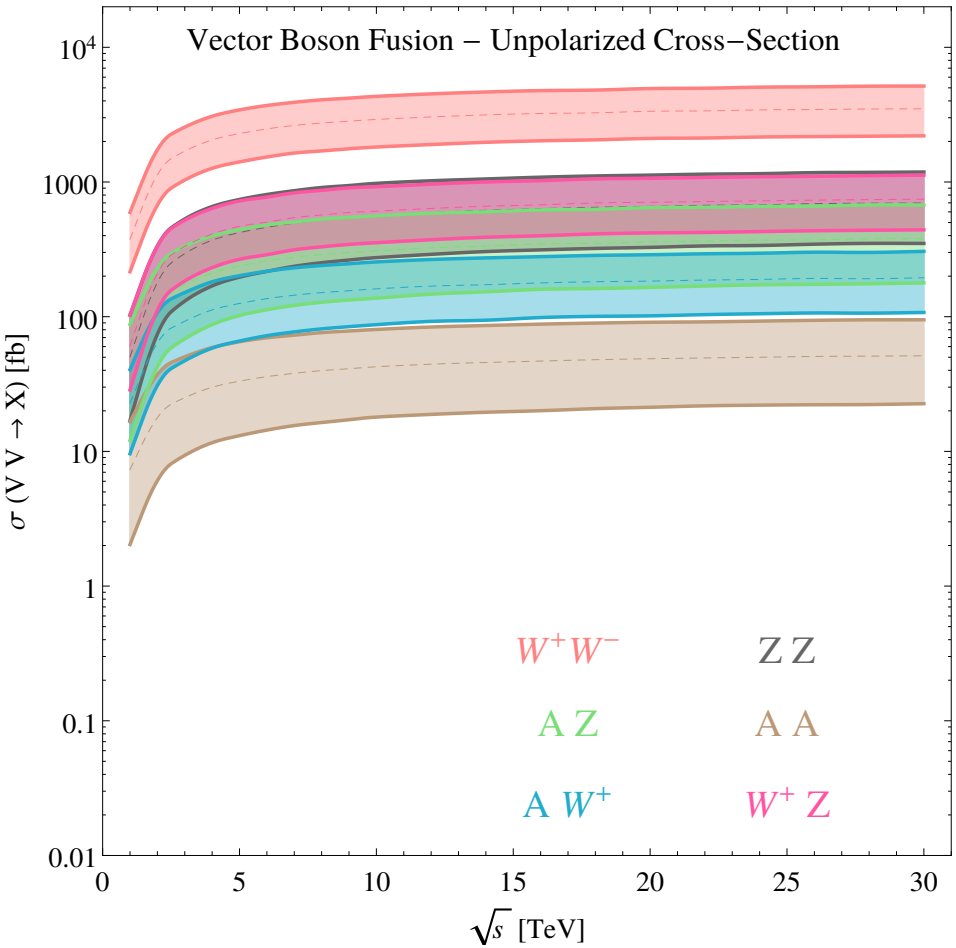
some results on

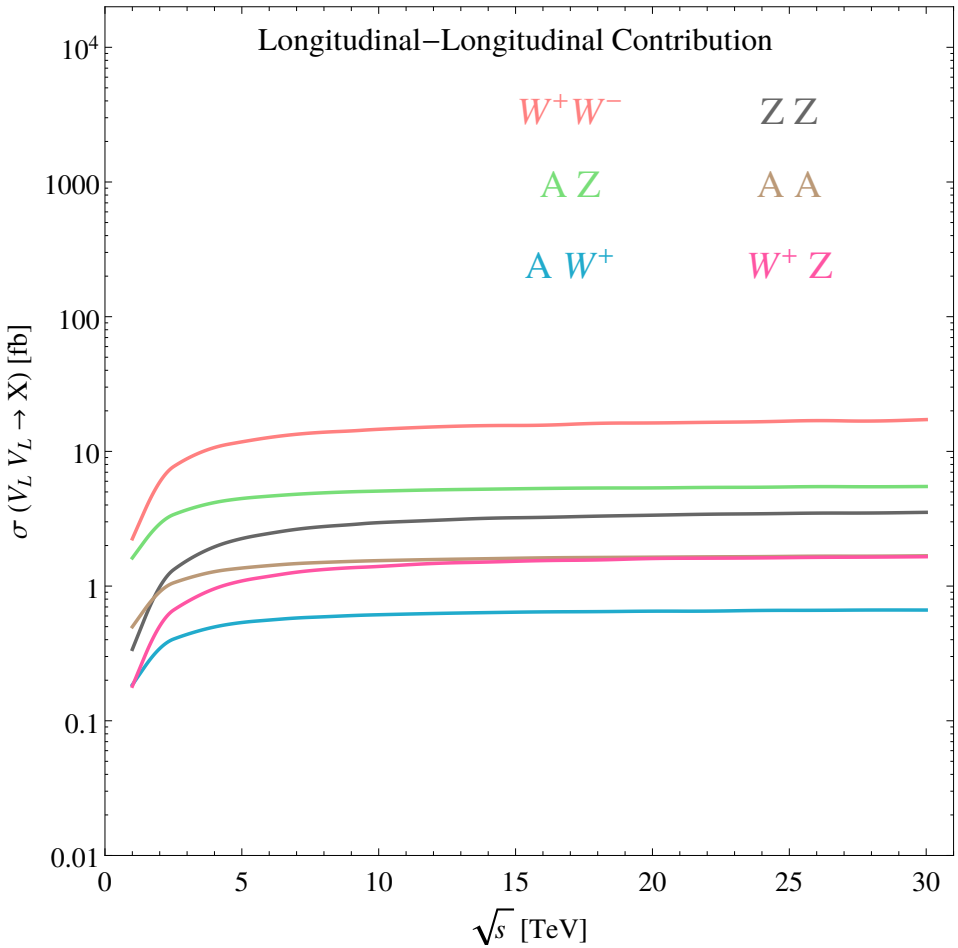
scattering of polarized EW bosons $V_\lambda V'_{\lambda'} \to X$ [5]

[5] w/ A. Costantini, F. Maltoni, L. Mantani, O. Mattelaer [2105.?????]

Diboson production

$V_\lambda V'_\lambda \to VV'$: (L) all polarizations (R) $V_0 V_0$

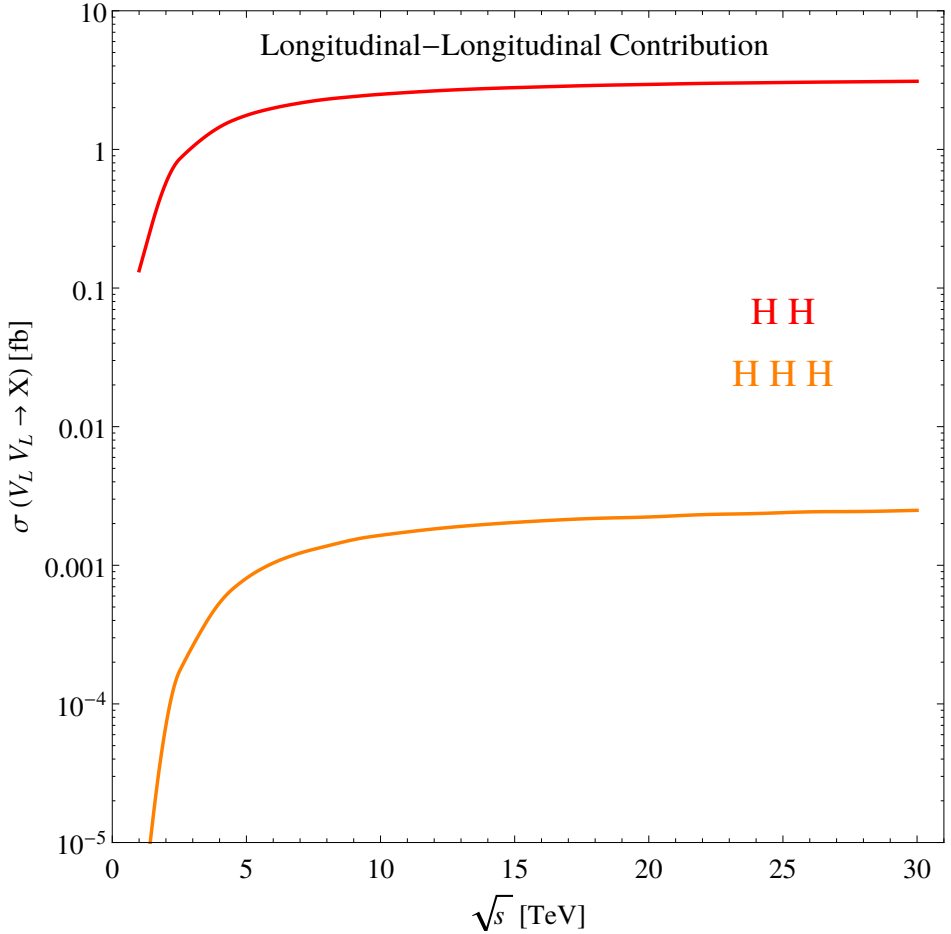


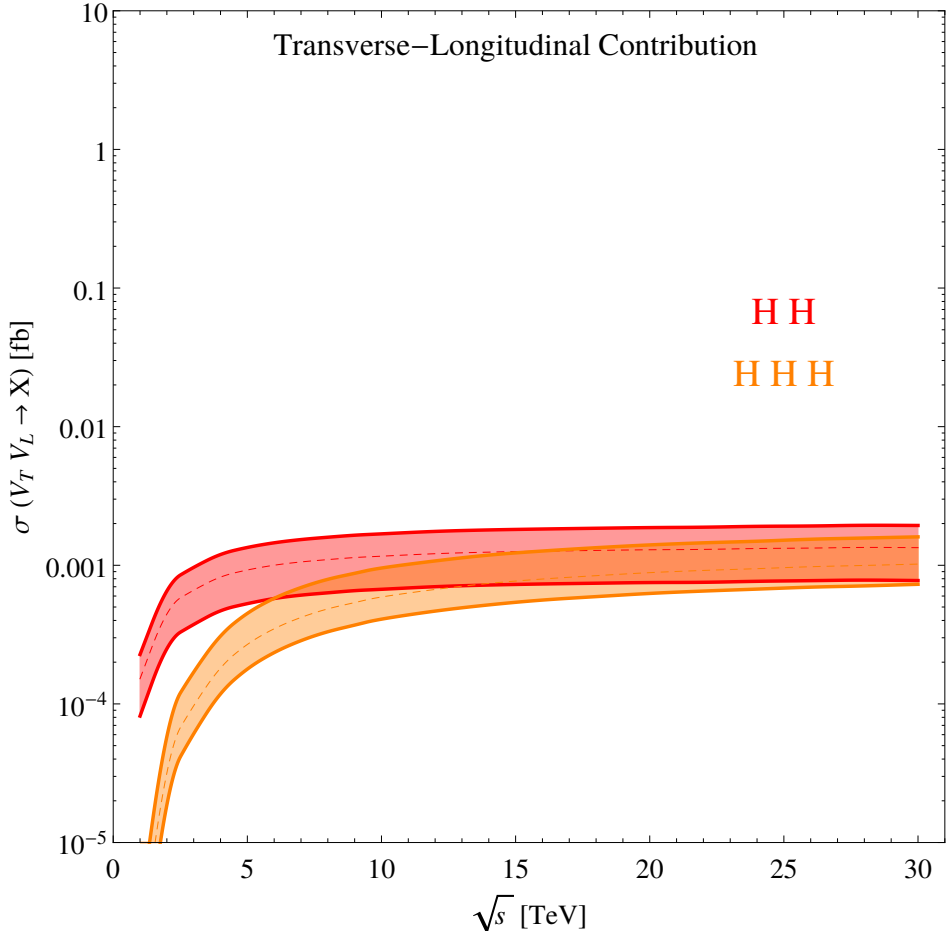


- Only minor role played by $V_0 V'_0$ scattering
- At $\mathcal{L} = 1\ \mathrm{ab}^{-1}/yr \implies 10^6\ WW/yr$ driven by non-Abelian couplings

MultiHiggs production

$V_\lambda V'_\lambda \to nH$: (L) $V_0 V_0$ (R) $V_0 V_T + V_T V_0$





- Importance of $V_\lambda V'_\lambda$ depends on number of H
- At $\mathcal{L} = 1\ \mathrm{ab}^{-1}/yr \implies 10^3\ HH/yr$ (incredibly rich physics!)

see backup for more plots!

Multi-TeV-scale muon colliders provide new perspectives on the building blocks of nature, particularly the μ flavor sector!

- Using full matrix elements, multi-TeV-scale muon colliders are effectively EW boson colliders (eventually, $\sigma^{VBF} \gg \sigma^{s}$)

  w/ A. Costantini, F. De Lillo, F. Maltoni, L. Mantani, O. Mattelaer, X. Zhao [2005.10289]

- Using EVA, $V_\lambda V'_{\lambda'}$ scattering reveal a new picutre of the EW sector at high energies (EVA in `MadGraph5` will be released soon!)

  w/ A. Costantini, F. Maltoni, L. Mantani, O. Mattelaer, et al [soon!]

- Polarized scattering amplitudes and cross sections now possible with `MadGraph5` simulation framework (not enough time to cover everything!)

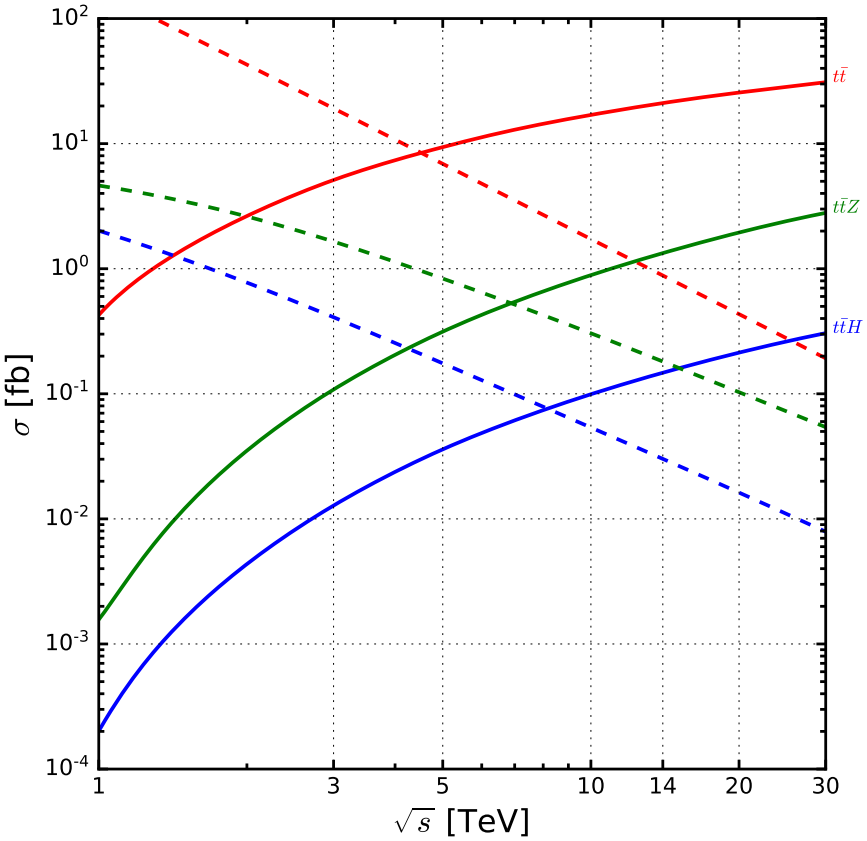
  w/ D. Buarque Franzosi, O. Mattelaer, S. Shil [1912.01725]

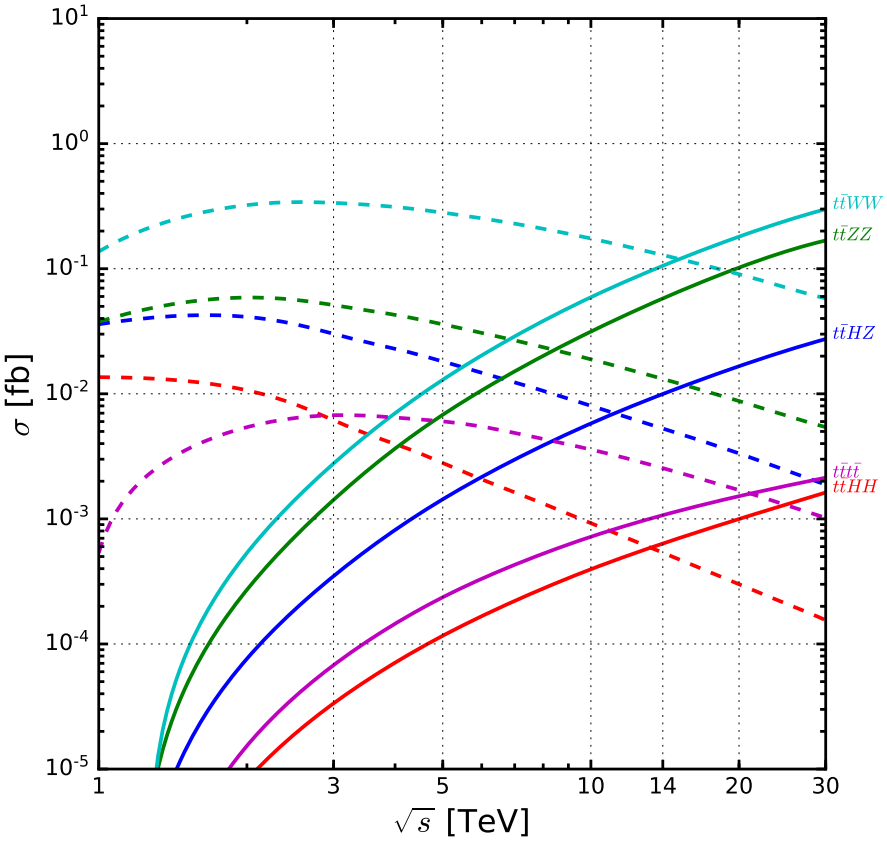
Thank you for listening!

Participation is possible with support from APS' Forum for Early Career Scientists Award! (Thanks FECS!)

Backup

Top quarks with full ME

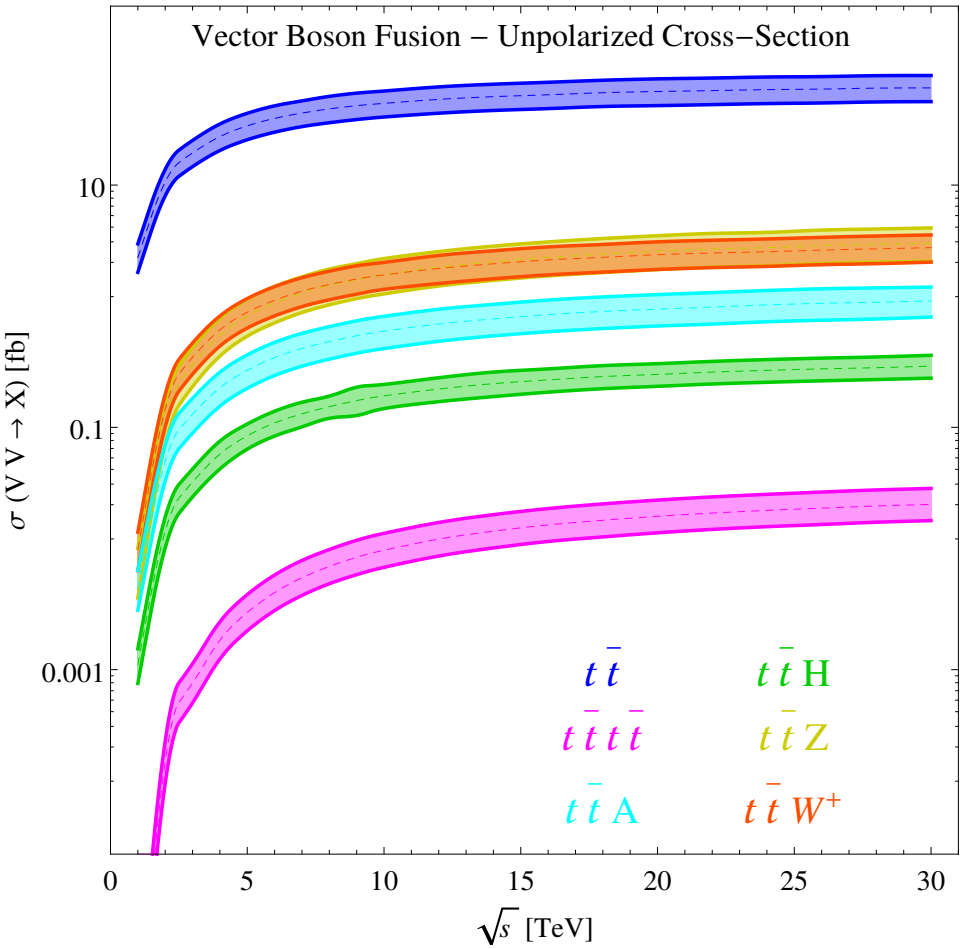


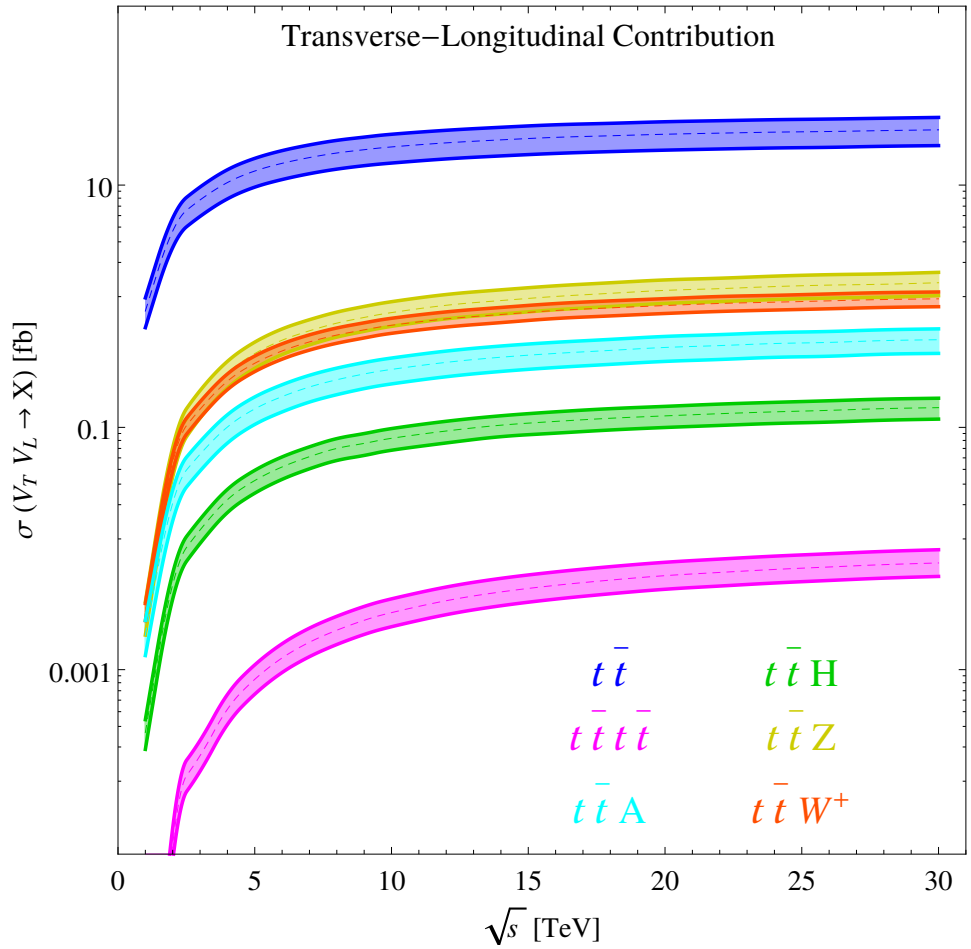


- Eventually, VBF is dominant production vehicle of EW states

Top quarks in EVA

$V_\lambda V'_\lambda \to t\bar{t} + X$: (L) all polarizations (R) $V_T V_0 + V_0 V_T$

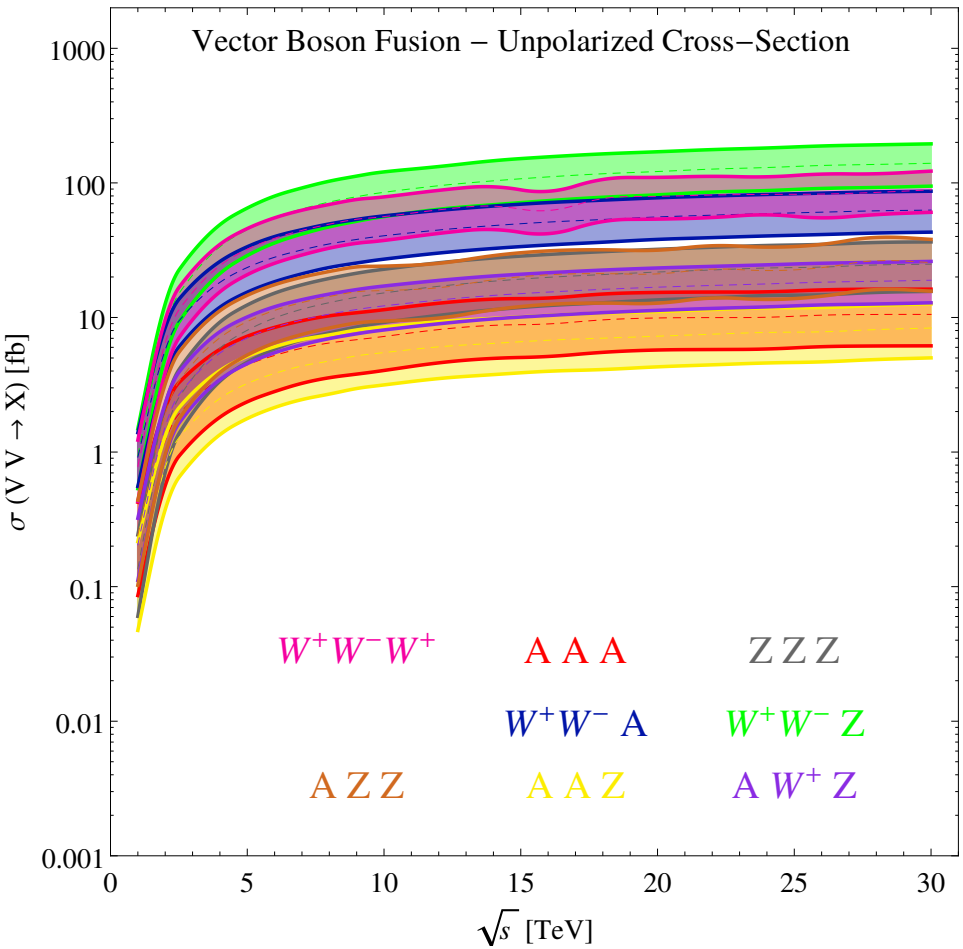


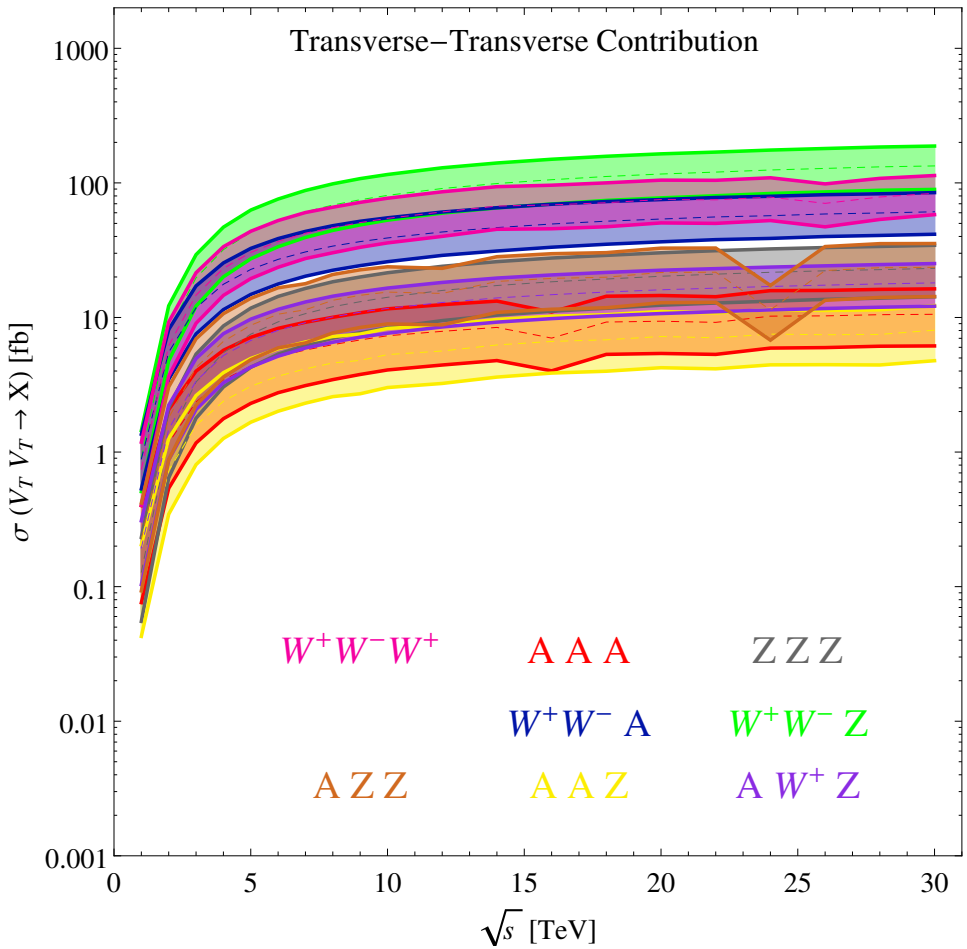


- Nontrivial contribution from all $V_\lambda V'_\lambda$ combinations
- Clear hierarchy of weak and EM couplings

Triboson production in EVA

$V_\lambda V'_\lambda \to VV'V''$: (L) all polarizations (R) $V_T V_T$





- Major role played by $V_T V'_T$ scattering
- At $\mathcal{L} = 1\ \mathrm{ab}^{-1}/yr \implies 10^3\ VV'V''/yr$